Report for 2002NE9B: ASSESSMENT OF THERMAL-INFRARED IMAGING AS A TOOL FOR EVALUATION OF GROUNDWATER-LAKE INTERACTIONS IN THE NEBRASKA SAND HILLS

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Report Follows:

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Statement of Critical Regional or State Water Problem. Many studies dealt with the Sand Hills lakes hydrology over the last decade. However, little is known about water exchange between the lakes and the aquifer in the context of the complete hydrologic system. Therefore, it is critical to investigate and expand the potential of innovative large-scale methodologies for studies of the Sand Hills hydrologic system.

Nature, Scope, and Objectives of the Project. There is a large body of theoretical and field investigations that indicates that localities of the groundwater recharge zones in lakes may be relatively conservative in space and in time. To a large degree the water-table configuration determines the presence of near-shore zones of this recharge (Winter, 1986). Previously, detection of such zones was based on inference of the hydraulic head gradients from network of observation wells in the vicinity of individual lake(s) (LaBaugh, 1986). This approach assumes availability of vast network of piezometer clusters that provide a fine resolution of head distribution in vertical and horizontal directions. In the Sand Hills, a very sparse network of wells is available, and potential of delineation of the water-exchange zones is limited.

The project exploited an idea of using temperature differences between groundwater and surface water in the Sand Hills lakes to delineate zones of extensive groundwater-surface water exchanges. The groundwater temperature is relatively stable, while the temperatures of the surface water are affected by diurnal and seasonal fluctuations due to several mechanisms. Analysis of the areal temperature patterns of the surface water is based on a search of anomalies that include zones of elevated or reduced temperatures compared with the ambient temperature. Groundwater discharge to the Sand Hills lakes may be manifested by zones of reduced temperatures in summer months, while zones of warmer temperatures are expected in winter months.

The general objective of this study was to evaluate thermal-infrared imaging as a tool for characterizing groundwater-surface water interactions between the lakes and the shallow aquifer of the Nebraska Sand Hills. The specific objectives were as follows:

- Collect and process data on surface temperatures for several lakes using TIR imaging to identify zones of active groundwater-surface water exchange and their orientation with respect to the regional flow;
- Collect data on the distribution of lake surface temperatures using ground methods and compare with remotely sensed TIR data;
- Compare results with previously collected remote sensing TIR data from several lakes;
- Assess the potential of the technique for upscaling data of groundwater-surface water interactions to a larger numbers of lakes and areas in the Nebraska Sand Hills

Related Research. In case of lakes that are strongly interconnected with the groundwater, the localized temperature anomalies of the surface water body may be affected by the water and heat exchange with the groundwater. Factors that affect this balance can be divided into water mixing (currents, wind speed and consistency, surface body depth) and heat transfer (solar radiation etc.). In addition, these factors may vary with seasonally and diurnally. For example, in case of rapid water currents, the insufficient contrast between the temperatures of the groundwater and surface water coupled with intensive mixing can obscure inflow of warmer or cooler water into the recharge zone that makes detection of groundwater recharge unfeasible. More quantitative approach can be affected by heat conduction, wind effects, thermal boundary layer effects and stratification during different seasons and times of day (LeDrew and Franklin, 1985; Torgersen et al., 2001).

Rundquist et al. (1985) pioneered the idea of using the TIR remote sensing for qualitative analysis of hydrology of flow-through lakes. They singled out four lakes in the Sand Hills with greater potential for inference of the zones of intensive groundwater seepage. Data from thermal-infrared multi-spectral (TIMS) airborne scanner in 8.2-12.2 micron range were obtained in 1983 and 1984 from NASA National

Space Technology Laboratory (NSTL) missions in Nebraska. Using channel with 8.2-8.6 micron, Rundquist et al. (1985) detected the thermal variability and possible groundwater discharge zones to these lakes. This study demonstrated feasibility of hydrologic inference from remote sensing data. Later TIR remote sensing was used in freshwater lakes to map surface temperature and circulation patterns (LeDrew and Franklin, 1985; Anderson et al., 1995; Garrett and Hayes, 1997).

Over the last decade, new technological capabilities of TIR remote sensing emerged that permit applications commonly available airborne platforms (small commercial planes and helicopters) instead of special NASA missions. These capabilities include commercially available TIR cameras (e.g., Thermacam™) operating in ranges 3-5 and 8-12 micron. Data collection of approximately 250 linear kilometers of continuous imaging can be accomplished with a budget of approximately $20/km when and where the appropriate infrastructure is available (McKenna, 2000).

The latest applications of TIR techniques include delineation of groundwater recharge to estuaries, stream temperatures due to groundwater recharge, surface temperatures and circulation patterns in lakes, land environmental effects of urban development in various climatic zones.

McKenna et al. (2001) applied TIR technique combining the ground-, aerial-, and satellite (LANDSAT 7, thermal band) imagery for delineation of groundwater discharge to the Rehoboth and Indian River bays, Delaware. Roseen et al. (2001) assessed the nutrient loading in the Great Bay estuary, New Hampshire using comparison of aerial methods with hydrogeological field measurements (piezometric mapping).

Recently, extensive studies of stream temperatures were carried out in Oregon (Torgersen et al., 2001) and Washington (Naveh et al., 2001, Handcock et al., 2001). Unlike in estuaries, lakes, or on the land surface, the length of surveyed areas (tens of kilometers) greatly exceeded the width (100 m) of the surveyed corridors along the streams. Therefore, the TIR remote sensing on the stream temperatures became the only feasible approach.

However, lake studies in the Sand Hills have seen limited applications of TIR techniques recently, and potential of these techniques needs assessment of these conditions.

Methods and Results. In search of large-scale approaches, we investigated if methods of satellite data collection and analysis have the potential for detection of groundwater discharge to the lakes in the Sand Hills area. This pilot study had a qualitative nature and attempted to find any manifestations of this discharge and to explore techniques that are valid for the Sand Hills conditions.

Direct temperature measurements. Lake temperatures were measured in three Sand Hills lakes (Crescent, Island, and Blue lakes) during four field surveys in summer 2002 using digital thermometer. Data were collected at 20-60 locations at each lake, depending on lake area. Measurements were made from the lake surface to the bottom with 20-cm depth increments. Resulting three-dimensional temperature distributions in the lakes allowed to locate zones of anomalously cooler water during summer season. These zones were considered as potential zones of groundwater discharge.

Relationship between thermal lake regime and weather conditions (air temperature and wind speed) was studied using submersible data loggers over several weeks with 30-minute measurement interval. Weather data (air temperature and wind speed) were obtained from online data bank of High Plains Regional Climate Center (HPRCC). Data loggers were installed in different parts of the lakes with different suspected magnitude and direction of fluxes between lake and aquifer.

Three types of temperature distribution in the Sand Hills lakes were found: 1) lake mixing as a result of strong wind, when water in a lake is thermally uniform in vertical direction from lake surface to bottom; 2) lake stratification as a result of higher air temperature compared to lake temperature when lake temperature is the highest in the upper layer and becomes lower with depth; 3) isothermal distribution when lake temperature is uniform in vertical direction in the absence of strong wind; this occurs primarily during night-time in summer when the air temperature is lower than lake temperature, and there is no groundwater discharge. Ground-based data allowed to locate zones where groundwater discharge can potentially occur and to study their thermal regime.

Remote sensing and GIS. Due to unavailability of the airborne TIR system, we utilized commercially available Landsat data. Satellite imagery was obtained from UNL Center of Advanced Land Management Information Technologies (CALMIT) imagery archive and from the USGS EROS data center. Available 21 Landsat images (satellites Landsat 4, 5, and 7) were taken from 1989 to 2002 in different seasons, mostly in the summer, but also in the fall, spring and winter time. All images were georeferenced. Only the Landsat thermal infrared band (10.40-12.50 microns) was processed and analyzed. Special algorithm was used in ERDAS Imagine software for recalculation of lake surface temperatures from pixel values (digital numbers). Atmospheric conditions were not taken into account, therefore, calculated temperatures were considered as uncorrected. Resulting uncorrected lake temperatures were used to identify patterns of surface temperature distributions in the studied lakes. Spatial resolution of the sensors on the Landsat satellites (60 and 120 m) and also thermal resolution of these sensors (0.4-0.6 ºC) allowed to distinguish patterns of relatively cooler water on summer and fall images and patterns of relatively warmer water on winter and spring images. These anomalous zones can be considered as indicators of potential groundwater discharge in the lakes.

To locate zones with consistently anomalous surface temperature, the following technique was applied. All available Landsat images were classified into two groups. The first group included 16 images with "warm season patterns" when groundwater temperature is supposed to be lower than the lake temperature (late spring, summer, and early fall seasons). Zones with cooler water on these images can be considered as the zones of potential groundwater discharge. The second group of 5 images included the "cold season patterns" when groundwater temperature is supposed to be higher than the lake temperature (late fall, winter and early spring seasons). Zones with warmer water on these images can be considered as the zones of potential groundwater discharge.

Each group was analyzed in ArcGIS 8.1software. The Landsat images were taken in different weather conditions and lake temperatures ranges. Therefore, lake temperatures were normalized as follows: $T_N = (T-T_{MIN}) / (T_{MAX}-T_{MIN})$, where T_N – normalized temperature; T – uncorrected temperature, calculated for each pixel; T_{MIN} – minimal uncorrected temperature in the lakes on the image; T_{MAX} – maximal uncorrected temperature in the lakes. These normalized temperatures ranged from 0 to 1 that made possible to analyze spatially all images together. Different statistics (mean, standard deviation and minimum) were calculated for each pixel location for warm and cold season images. This resulted in finding of several anomalous zones in each lake that can be considered as the potential zones of groundwater discharge. Future studies should include direct measurements of groundwater-lake water exchange across the lakebeds.

Major Findings. Thermal infrared imaging was assessed for evaluation of groundwater-surface water interactions by comparing satellite (Landsat) images with ground-based temperature data. Detailed three-dimensional temperature distributions for several Sand Hills lakes were obtained from ground-based studies for summer time and anomalous thermal zones were located. In these zones lake water is generally cooler and they can be considered as groundwater discharge zones. Dependence of thermal regime of the lakes on weather conditions was studied and three principal types of thermal distributions in the Sand Hills lakes were distinguished (lake mixing, lake stratification and isothermal vertical distribution). Numerous Landsat thermal infrared images were processed and analyzed, and lake temperature patterns were studied. Spatial analysis of thermal infrared images in ArcGIS allowed to identify zones in the lakes where lake water was consistently cooler during warm season. These zones which are considered as the potential zones of groundwater discharge are generally located in the same parts of the lakes as the zones which were found after field-based surveys. These data refined findings from TIMS surveys of the summer thermal lakes patterns obtained in 1983-1984. Therefore, thermal infrared remote sensing has a potential for identification of the groundwater discharge zones in the shallow groundwater-fed Sand Hills lakes.

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